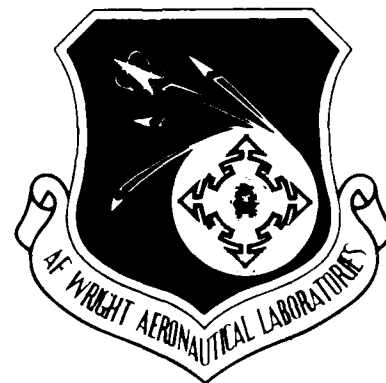


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A COMPARATIVE EVALUATION OF RPD AND FERROGRAPHIC DIAGNOSTIC
METHODS FOR TURBINE ENGINE LUBRICANT SAMPLES

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Robert L. Wright
Lubrication Branch
Fuels and Lubrication Division

March 1988

Final Report for Period May 1987 - September 1987

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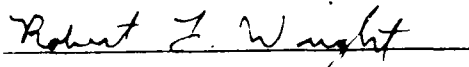
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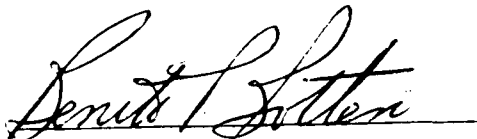
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for Public Release: Distribution Unlimited		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFWAL-TR-88-2020			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Aero Propulsion Laboratory	6b. OFFICE SYMBOL (If applicable) AFWAL/POSL	7a. NAME OF MONITORING ORGANIZATION			
6c. ADDRESS (City, State, and ZIP Code) Air Force Wright Aeronautical Lab (AFSC) Wright-Patterson AFB OH 45433-6563		7b. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB OH 45433			
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Aero Propulsion Laboratory	8b. OFFICE SYMBOL (If applicable) AFWAL/POSL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER			
8c. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB OH 45433-6563		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO. 62203F	PROJECT NO. 3048	TASK NO. 06	WORK UNIT ACCESSION NO. 26
11. TITLE (Include Security Classification) A Comparative Evaluation of RPD and Ferrographic Diagnostic Methods for Turbine Engine Lubricant Samples					
12. PERSONAL AUTHOR(S) Robert L. Wright					
13a. TYPE OF REPORT Final	13b. TIME COVERED FROM 87/5/12 TO 87/9/30	14. DATE OF REPORT (Year, Month, Day) March 1988	15. PAGE COUNT 28		
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Rotary Particle Depositor, Ferrography, Wear Debris, Lubricant Analysis, Turbine Engine Lubricant Analysis		
11	08				
14	02				
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>A rotary Particle Depositor (RPD) was evaluated and compared to analytical (AF) and direct reading (DR) ferrographs to ascertain if the RPD is better suited for analysis of wear debris in turbine engine lubricant samples than the AF and DR. Experimentally, sieved iron particles were added to synthetic turbine engine lubricants at various concentrations and analyzed by RPD and ferrographic methods and compared. Also, lubricant samples containing a fine test dust were analyzed by RPD and AF to determine the effectiveness of the RPD's centripetal acceleration and the AF's gravity flow in eliminating non-ferrous contamination from the sample. Finally, actual lubricant samples from a turbine engine simulator were analyzed by RPD and ferrographic methods and compared.</p> <p>For lubricant samples with relatively small amounts of non-ferrous contamination or samples where non-ferrous particles are important in machine health condition assessment, the AF and DR ferrographs are equal or superior to RPD for lubricant analyses. For samples with high levels of non-ferrous contamination, the RPD is superior in eliminating unwanted</p>					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL ROBERT L. WRIGHT			22b. TELEPHONE (Include Area Code) (513) 255-3551	22c. OFFICE SYMBOL AFWAL/POSL	

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non-magnetic particles and permitting a less obstructed view of the important ferrous wear debris particles.

PREFACE

This technical report was prepared by the Lubrication Branch, Fuels and Lubrication Division, Aero Propulsion Laboratory (APL), Air Force Wright Aeronautical Laboratories (AFWAL), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio. The work was accomplished under Project 3048, Task 304806, Work Unit 30480626, "Turbine Engine Lubricant Research," during the period of May 1987 to September 1987 with Mr Robert L. Wright as project engineer.

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SECTION I

INTRODUCTION

The primary diagnostic methods in use today for the analysis of engine wear debris particles found in lubricants are the analytical (AF) and direct reading (DR) ferrographs (1). Although useful tools, AF and DR have shortcomings. Much non-ferrous debris, such as contaminant dirt particles, can be gravimetrically trapped on the AF slide (ferrogram) or larger particles may be retained in the delivery tubing, and the analytical costs of the AF are significant. DR is strictly used for quantitative particle measurement. The rotary particle depositor (RPD) (2) was developed as a less costly approach for situations where non-ferrous debris content is high, and uses centripetal acceleration and direct pipetting of the lubricant sample onto the slide to alleviate gravimetric trapping and tubing particle retention problems associated with ferrography. Permanent magnets trap ferrous particles in a three-ring pattern as the circular slide and magnets spin together at a pre-determined rate. All sizes of particles are trapped around the inner ring, while intermediate and small sized particles are trapped around the second ring, and only very small particles are captured at the outer ring. Much of the non-ferrous material is removed from the slide by centripetal acceleration, allowing for unobstructed viewing of the important ferrous wear particles by the laboratory analyst. This effort was an attempt to determine if the RPD could be used alone or in concert with AF and DR ferrographs to better analyze turbine engine lubricant samples.

SECTION II

EXPERIMENTAL PROCEDURE

Sieved iron particles in size ranges of interest (0-44, 5-10, 10-20, and 30-44 micrometer) were added to a typical ester based turbine engine lubricant (MIL-L-7808) (3) at concentrations of 50, 100, and 200 parts per million (ppm). These prepared oil samples as well as samples that were purposely contaminated with AC fine test dust (4) (silica particles of size range: less than 1 to 80 micrometers) and a sample from a J-57 jet turbine engine simulator after 250 hours of operation were all analyzed on AF, DR and RPD. A standard procedure was used to prepare each oil sample for AF, DR and RPD analyses. This consisted of vigorously hand shaking the sample for 30 seconds then heating the oil to $65 \pm 5^\circ\text{C}$. After heating, the sample was again vigorously hand shaken for 1 minute and then immediately analyzed. Depending upon particle concentration, the amount of undiluted sample analyzed varied from 0.1 to 3 milliliters, although the total volume analyzed was held at 3 ml for AF and RPD and 1 ml for DR by addition of the proper amount of clean diluent oil. Standard ferrograph operating procedures (5, 6) were used for all AF and DR analyses. Standard operating procedures were used for all RPD analyses (2), except that the rotational speed for sample deposition onto the RPD slide was chosen to be 110 revolutions per minute (rpm) instead of the recommended 70 rpm. This was done because 110 rpm appeared to generate the desired ring deposition pattern better than several other settings that were attempted between 70 and 200 rpm.

After each AF analysis, the sample ferrogram was examined under the ferroscope and the percent area covered (PAC) by wear particles at

selected slide positions was measured by ferrogram reader photodensitometer. The ferrograms were measured for PAC at the entry point, 50 mm, and 10 mm from ferrogram exit positions. Zero readings were taken at a particle free point on the ferrogram above or below the positions of interest, as standard procedure recommends. Photodensitometer large particle readings (D_L) and small particle readings (D_S) were recorded for each DR analysis. Each RPD sample slide was examined under the ferroscope and since a magnetic moment particle quantifier that is commonly used to quantify particle concentration on an RPD slide was not available, a method was developed for measuring the PAC of deposits on the RPD slide by use of the ferrogram reader photodensitometer. This was done by using the cone of light exiting from the ferroscope 11X eyepiece to visually approximate the position of the center of the innermost deposition ring on the RPD slide. A more exact centering of the beam was then accomplished by maximizing the ferroscope stage x and y measurements with respect to the inner ring. The intersection point of these x and y lines was noted and taken as the center-point of the slide. A zero reading was taken here or at a particle free point nearby. The slide was then moved along the y axis until the innermost ring deposits were in view. This y change from center was noted and designated as the 0 degree position. A PAC reading was taken here and then the slide was moved back to the center coordinates. From here, the slide was moved along the x axis until the innermost ring deposits were in view. This was designated as the 90 degree position and a PAC reading was taken here. This procedure was repeated to obtain readings at the 180 and 270 degree positions. The arithmetic mean value of the four readings was entered as the PAC value

for the ring in question. The procedure was then repeated on the second and outer deposit rings, if they were present. This procedure was necessary because the RPD deposit rings were observed to be non-homogeneous in particle deposit density around the ring.

SECTION III

RESULTS AND DISCUSSION

In each iron particle size range, samples in 50, 100, and 200 ppm concentration were carefully prepared. Figure 1 shows a scanning electron micrograph (SEM) of the original iron powder used in this investigation (0-44 micrometer particles). The particles are seen to be irregularly shaped but tending toward semi-spherical in shape. Approximately 10 milligrams (mg) of iron was weighed out into an inert plastic sample bottle using an analytical balance with accuracy ± 0.0001 g for the 50 ppm samples. The proper amount (about 200 g) of MIL-L-7808 lubricant was then added to the sample bottle using a laboratory balance with accuracy ± 0.01 g to bring the sample to the desired 50 ppm concentration. All samples were in approximately 200 g of lubricant, so the amount of iron weighed out for the 100 and 200 ppm prepared samples was about 20 and 40 mg, respectively. The fractional iron concentration is then simply determined by the equation:

$$C = m_{Fe} / (m_{Fe} + m_l) \text{ or } m_{Fe} / m_l \text{ (since } m_l \gg m_{Fe})$$

where: C = sample iron concentration (fractional)

m_{Fe} = mass of the iron

m_l = mass of the lubricant = 200 g

To determine the uncertainty in the concentrations, the uncertainty equation of Kline and McClintock (7) is used:



Figure 1. Iron particles used in prepared samples, 0 - 44 μm

$$w_C = [(\partial C / \partial Fe \times w_{Fe})^2 + (\partial C / \partial l \times w_l)^2]^{1/2}$$

where: w_C = uncertainty in the sample concentration

$\partial C / \partial Fe$ = partial derivative of the concentration with respect to the mass of the iron

w_{Fe} = uncertainty in the mass of the iron = ± 0.0001 g

$\partial C / \partial l$ = partial derivative of the concentration with respect to the mass of the lubricant

w_l = uncertainty in the mass of the lubricant = ± 0.01 g

From the concentration equation, one sees that $\partial C / \partial Fe = 1/m_l$ and $\partial C / \partial l = -m_{Fe}/m_l^2$. In this case, the second term on the right hand side of the uncertainty equation becomes insignificant and the uncertainty in the iron concentration of the samples is determined by the much simpler equation:

$$w_C = w_{Fe}/m_l$$

So one finds that the uncertainty of all samples is ± 0.5 ppm. The error in the concentration of each sample is then easily determined by dividing the uncertainty by the nominal iron concentration. When this is done, the errors for the 50, 100, and 200 ppm samples are ± 1.0 , ± 0.5 , and ± 0.25 percent, respectively. One sees that with these small errors in concentration, any variation in attempted quantitation of these

particles by photodensitometer after AF, DR or RPD analyses cannot be attributed to errors in sample preparation.

Attempts were made to correlate PAC readings normalized for sample volume to iron concentration for the prepared samples. Constant sample volume was maintained for each sample analyzed on each instrument. Only PAC readings at the entry point of the ferrogram and around the inner ring of the RPD slide and D_L readings of the DR analyses were used because there were virtually no particles captured beyond these regions for the prepared samples. The results for AF and RPD analyses are plotted as PAC reading per ml versus gravimetric iron concentration in Figure 2. The data are quite scattered, but three general trends seem to emerge. First, the PAC/ml reading for a given concentration decreases as particle size increases. This is because the surface area to volume ratio per unit mass increases as particle size decreases and a greater area of the sample slide is covered by smaller particles than by larger particles for each unit mass of material deposited. This trend doesn't hold, though, for the RPD analysis of the 10-20 micron particles in 200 ppm concentration. This data point lies above the 5-10 micrometer particle data point in the same concentration. This aberration and other apparent inconsistencies in the data are probably due to the often high relative standard deviation in PAC reading for ferrographic type deposits and the fact that the samples were analyzed by two different operators (8). Secondly, the data scatter increases as concentration increases. This is likely because the probability of a particle settling atop another is increased at larger concentrations and this effect will decrease PAC/ml and increase uncertainty in PAC readings.

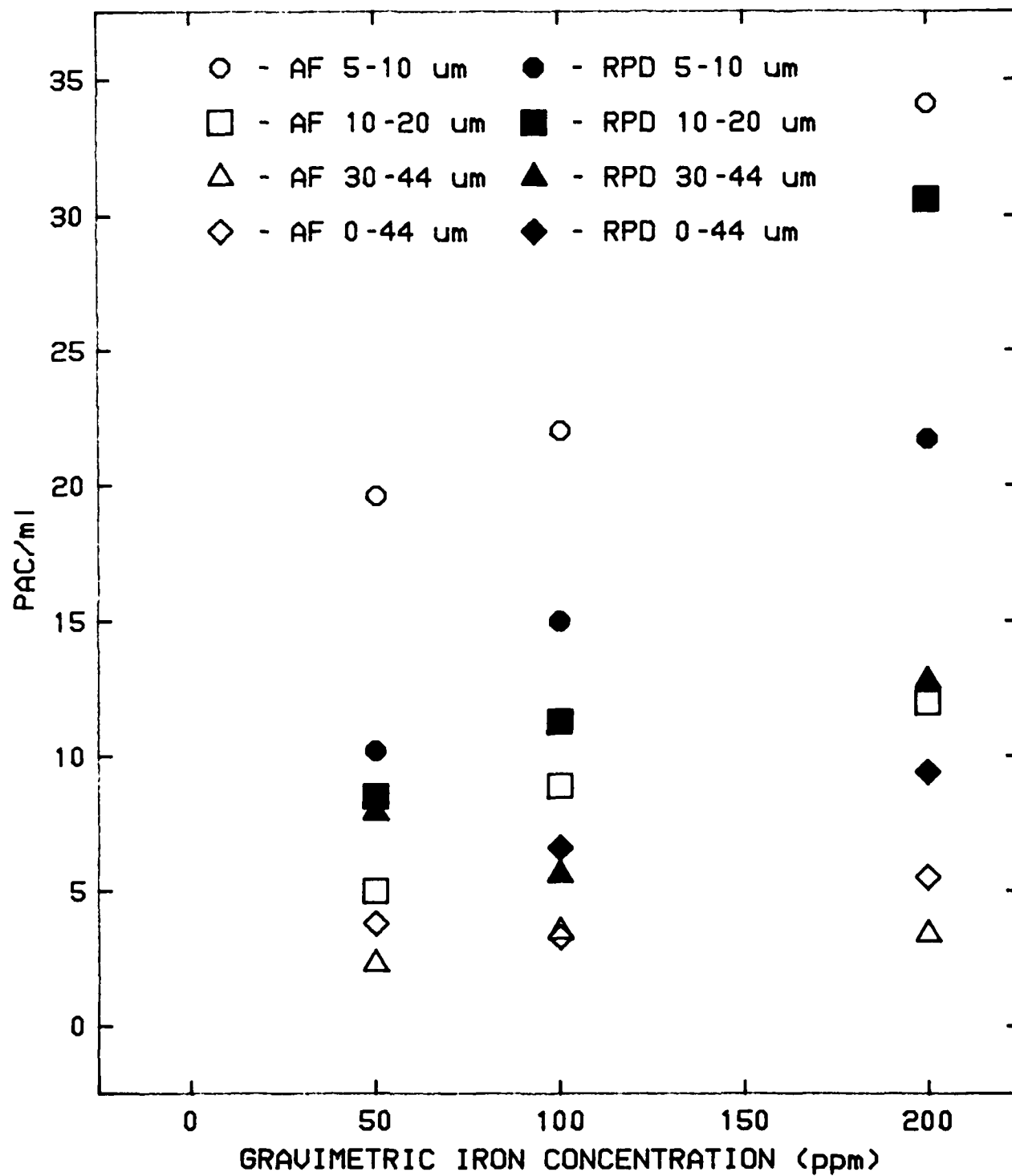


Figure 2. Prepared sample PAC/ml values vs. gravimetric iron concentration

Thirdly, PAC readings do not increase linearly with particle concentration. This is because the PAC vs. particle volume relationship is a power law rather than a linear function (8). It should also be noted that the PAC/ml readings are greater for the 5-10 micrometer particles on the ferrogram than on the RPD slide, while for all the rest of the prepared samples, the readings are greater for the RPD slides. This may be due to some of the larger particles being trapped in the AF delivery tubing and never getting deposited on the ferrogram. The results of DR analyses of these prepared samples are shown in Figure 3 as D_L readings versus gravimetric iron concentration.

As mentioned previously in the experimental section, the deposits on the RPD slide were observed to be non-homogeneous around the ring. To assess deposit variations around the RPD ring, the 5-10 micrometer particle sample at the 100 ppm concentration level was analyzed three times by RPD. PAC readings were taken at every 45 degrees around the inner ring (8 readings for each sample ring) of each RPD sample slide. The percent deviation of each PAC reading from its particular ring's mean PAC value is illustrated in Figure 4. This shows that particle deposit density is very non-homogeneous around the ring and justifies using at least four PAC readings around each deposit ring to arrive at a representative PAC value. The average radius of the inner ring deposits for all samples analyzed was 4.0 ± 1.1 mm. The average radius for the second ring was 6.7 ± 1.1 mm and the average radius for the outer ring was 9.4 ± 0.4 mm.

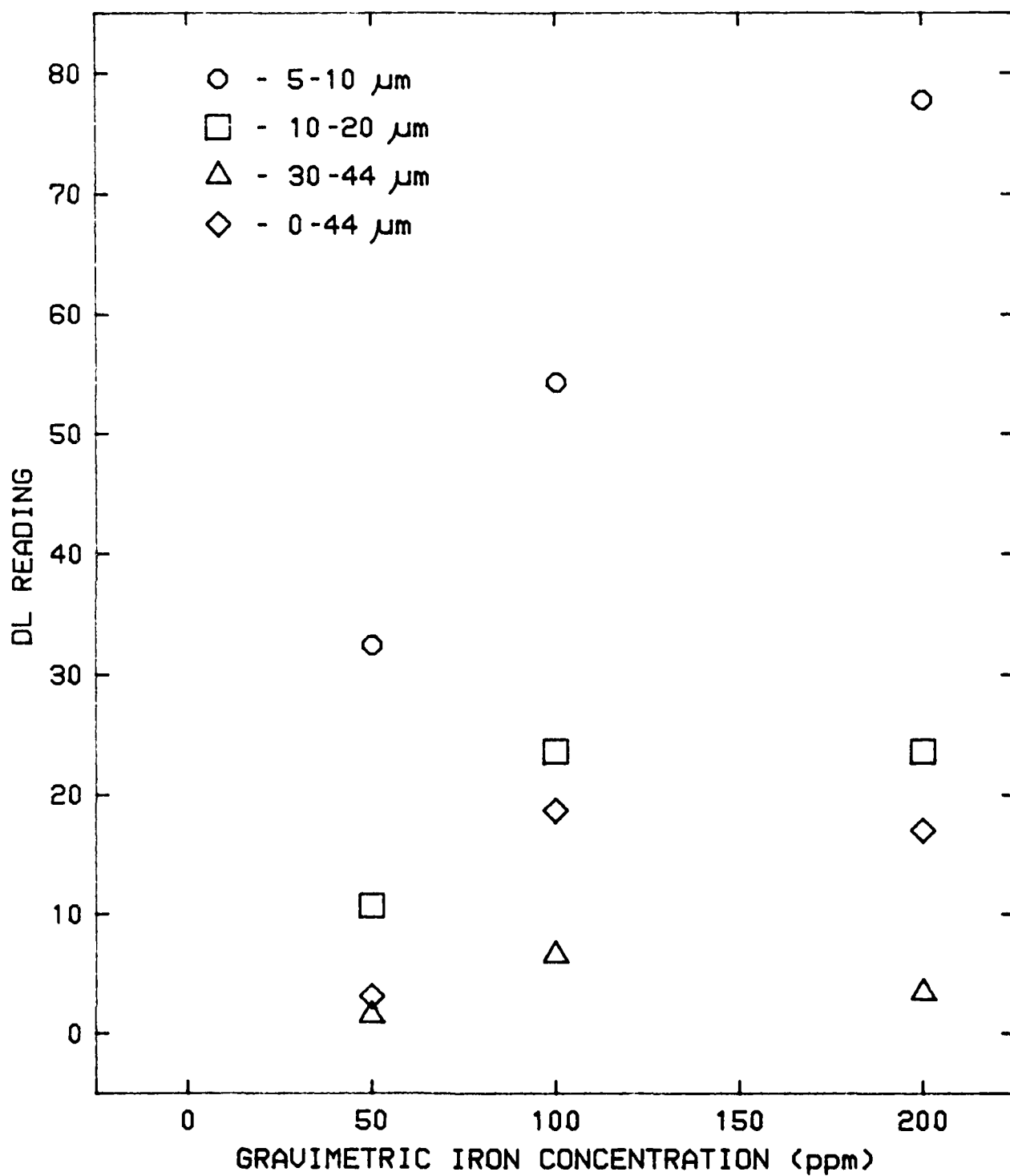


Figure 3. Prepared sample D_L readings vs. gravimetric iron concentration

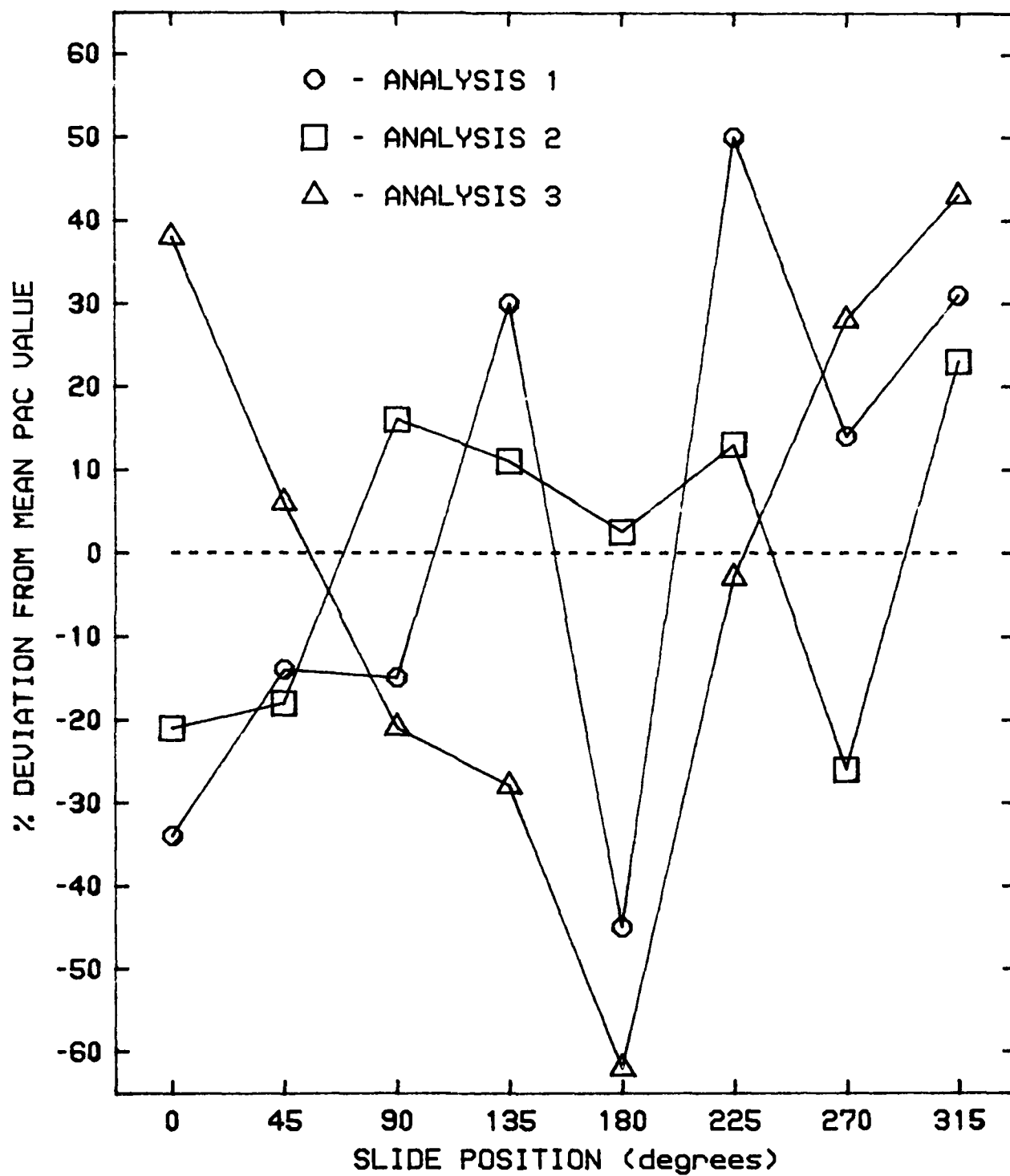
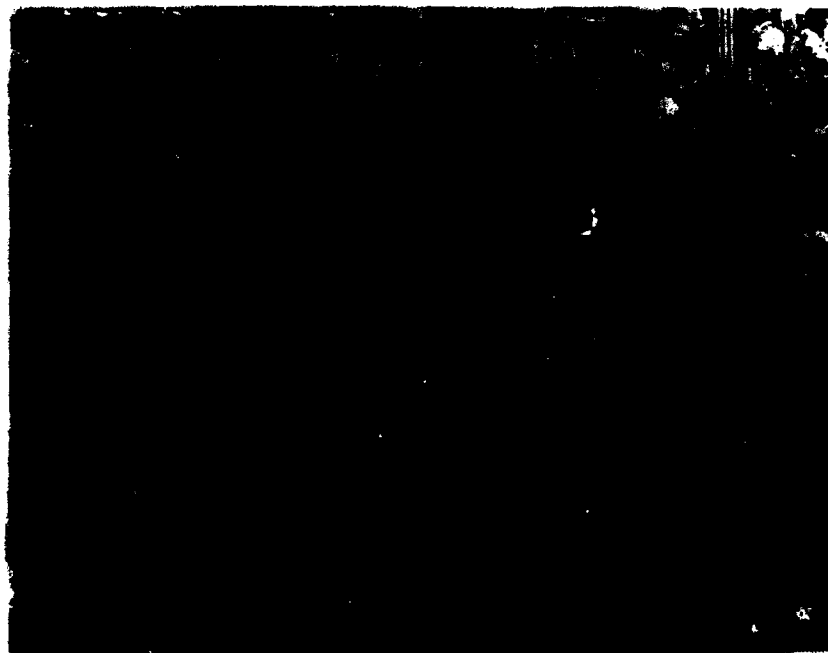


Figure 4. RPD percent deviation from mean PAC value vs. slide position

The 100 ppm, 5-10 micrometer particle sample was again used to prepare a new sample that was purposely contaminated with 500 ppm of the AC fine test dust. The new sample was analyzed on AF and RPD to determine if contaminant particles would interfere with the deposition and visual observation of important ferrous wear particles on either or both instrument's sample slides. The results of these analyses are shown by SEM comparison of the contaminated and uncontaminated ferrograms in Figure 5 and S·M comparison of the contaminated and uncontaminated RPD slides in Figure 6. It is seen that the contaminant particles show up in high concentration on the ferrogram and that the concentration of the ferrous particles appears much lower than that for the uncontaminated ferrogram. Most of the ferrous particles in the contaminated sample were either deposited much further down the ferrogram than for the uncontaminated sample or washed completely off the slide. The contaminated RPD slide, on the other hand, shows fewer of the contaminant particles, but many of the ferrous particles are not magnetically aligned. This magnetic alignment problem is not displayed by the contaminated ferrogram. The concentration of ferrous particles retained on the contaminated sample slide, however, is much closer to the uncontaminated sample slide concentration for RPD than for AF analysis. Apparently, the centripetal acceleration of the RPD is removing most of the non-ferrous contaminant from the slide, while the gravity flow of the AF allows much more of the contaminant to be captured on the ferrogram. In both cases, though, the contaminant particles appear to attenuate magnetic field strength, causing somewhat random particle distribution on the slides. Even with the randomly aligned particles, though, it is easier to see individual ferrous

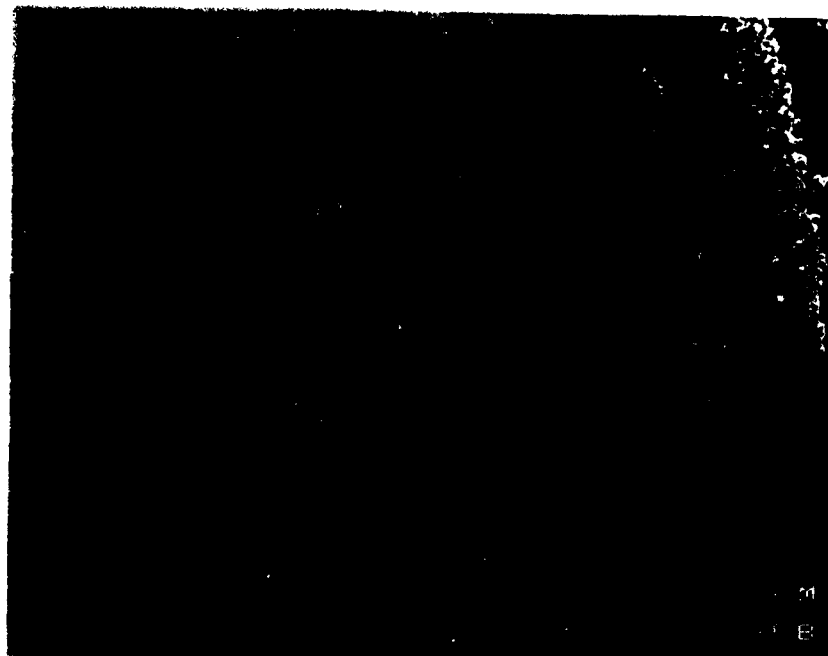


a) Uncontaminated ferrogram (entry point)

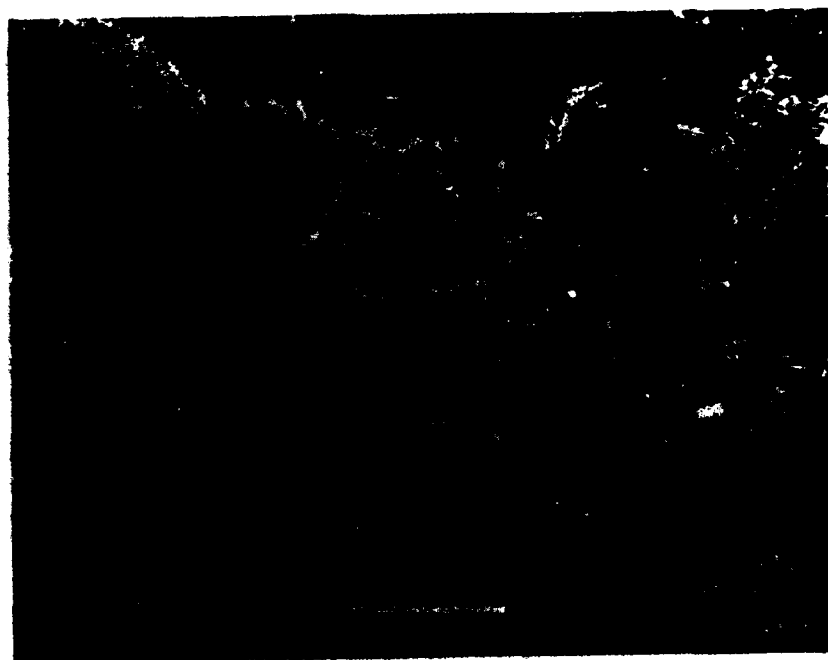


b) Contaminated ferrogram (entry point)

Figure 5. SEM comparison of contaminated and uncontaminated prepared sample ferrograms



a) Uncontaminated RPD slide (inner ring)

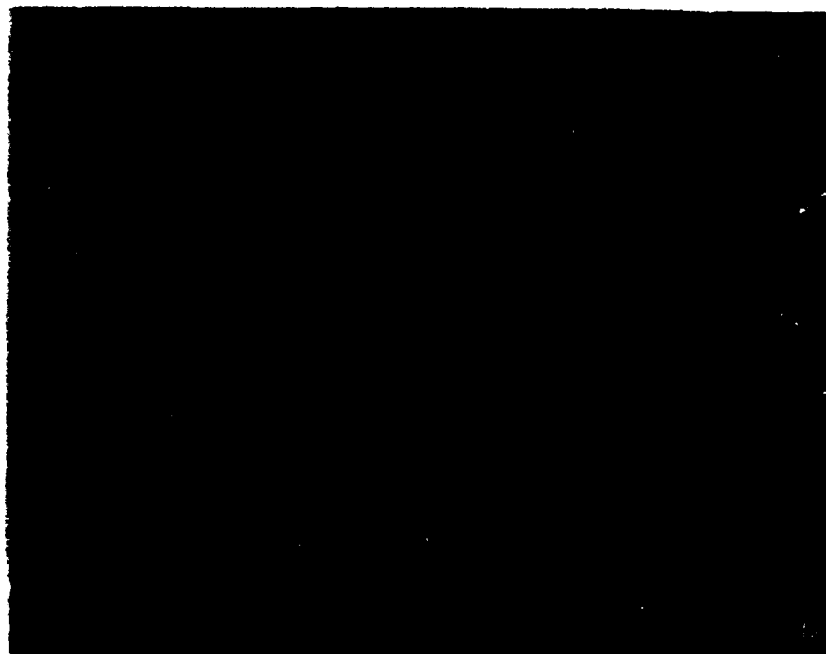


b) Contaminated RPD slide (inner ring)

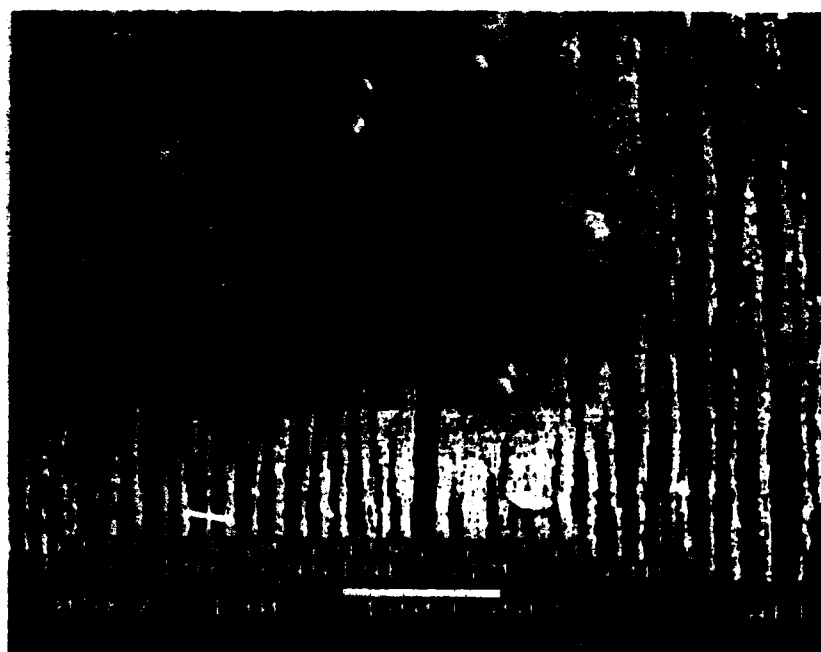
Figure 6. SEM comparison of contaminated and uncontaminated RPD slides

particles on the RPD slide because there are many fewer contaminant particles to physically obstruct the analyst's view. This confirms the work of Price and Yardley (9) with AF and RPD analyses of lubricant samples from gear transmissions operating in a highly contaminated underground environment, although they did not report having particle alignment problems on the RPD slide. A comparison by SEM of RPD and AF analyses of the turbine engine simulator sample is shown in Figure 7. Evidence of severe wear can be seen in both micrographs, and evaluation of wear mechanism(s) can probably be equally well determined by use of either instrument. One notices, though, that the ferrous particles are more evenly aligned on the ferrogram, perhaps allowing for easier identification of ferrous and non-ferrous debris. It should be noted that the quantity and type of wear debris in this sample is not typical of turbine engines in general. Indeed, this sample was chosen because it contains a large quantity of abnormal wear debris that would be easily seen by AF and RPD analyses. The cause of the atypical debris quantity and type was a clearance problem in a mainshaft bearing (10).

Repeatabilities of the AF, DR, and RPD were evaluated by finding the relative standard deviations of the PAC/ml readings for the ferrograms and RPD slides and the large and small particle readings of the DR using the 100 ppm concentration samples for both the 5-10 micrometer and 30-44 micrometer particle size samples and also the turbine engine simulator sample. There were at least 4 analyses of each sample on each instrument at constant undiluted and total sample volume, and the $n-1$ standard deviations were used. The relative standard deviation was the $n-1$ standard deviation divided by the arithmetic mean



a) Turbine engine sample RPD inner ring



b) Turbine engine sample ferrogram entry point

Figure 7. SEM comparison of RPD slide and ferrogram for turbine engine sample

PAC/ml. The results are presented in Table 1. For the prepared samples, one sees that the AF and RPD repeatabilities are poor but of about the same magnitude for the 5-10 micrometer particle sample, and that repeatabilities are even poorer for the 30-44 micrometer particle sample. The RPD repeatability here is much better than that for the AF, giving credence to the hypothesis that some of these larger particles may be trapped in the AF delivery tubing. The table also shows that the repeatabilities are poor but are of the same magnitude for AF and RPD at the entry and inner ring deposits of the turbine engine simulator sample, but that the AF is more repeatable for the other slide positions measured. In both types of samples, the quantitation by AF and RPD is not reliable. It is also seen from Table 1 that repeatability is much better by DR than either AF or RPD, except for the case of the large, 30-44 micrometer particle sample.

Even though quantitation of lubricant sample wear debris by photodensitometer after AF and RPD analyses is unreliable in many cases, the most important application of these instruments is the subjective analysis of wear particles to deduce wear mechanisms and determine equipment health. Evaluation of these wear particles is a matter of experience and knowledge of the specific equipment whose sample is under analysis. If the proper experience and knowledge are available, then either the AF or RPD is an excellent tool to qualitatively evaluate equipment wear dynamics. Which instrument is the best choice for an analyst to use is dependent upon the application and type of sample in question. For quantitation of debris by photodensitometer for the samples identified here, DR was significantly better than AF in all cases, and significantly better than RPD for all but the case of extremely large, 30-44 micrometer particles.

TABLE 1 INSTRUMENT REPEATABILITIES

<u>SAMPLE</u>	<u>INSTRUMENT</u>	<u>POSITION/VALUE</u>	<u>PAC RELATIVE STANDARD DEVIATION (%)</u>
PREPARED	AF	ENTRY POINT	26
5-10 MICROMETER			
100 ppm Fe			
"	RPD	INNER RING	25
"	DR	D_L	11
PREPARED	AF	ENTRY POINT	100
30-44 MICROMETER			
100 ppm Fe			
"	RPD	INNER RING	45
"	DR	D_L	49
TURBINE ENG.	AF	ENTRY POINT	23
"	RPD	INNER RING	18
"	DR	D_L	9.5
"	AF	50 mm	24
"	RPD	SECOND RING	110
"	DR	D_S	10
"	AF	10 mm	13
"	RPD	OUTER RING	41

SECTION IV

CONCLUSIONS

Analysis of experimental lubricant samples by AF and RPD revealed that quantitation of wear debris is often difficult due to inherent repeatability problems, but is about equal for either technique and dependent upon particle size, morphology, and operator technique. Both techniques were found to be excellent for the qualitative evaluation of particle morphology, wear mechanism and equipment health. RPD was found superior for analysis of samples with high contaminant concentrations, but AF was equal or superior to RPD for all other situations. DR ferrograph photodensimetric quantitation of wear debris was more repeatable than either AF or RPD and was also found to be dependent upon particle size, morphology and operator technique. Ferrography appears to be the method of choice for turbine engine lubricant sample analysis, because of the typically low levels of non-ferrous contaminant debris encountered.

REFERENCES

1. Seifert, W. W. and Wescott, V. C., "A Method for the Study of Wear Particles in Lubricating Oil," *Wear* 21 (1972), 27-42.
2. Price, A. L. and Roylance, B. J., "The Rotary Particle Depositor - A Response to Problems Associated with Wear Particle Deposition," *Maint. Management Int.*, 5 (3) 1985, 187-193.
3. Military Specification, MIL-L-7808J, Lubricating Oil, Aircraft Turbine Engine, Synthetic Base (May 1982).
4. Wear Control Handbook, Peterson, M. B. and Winer, W. O., Eds., American Society of Mechanical Engineers, New York, NY (1980), 519.
5. Standard Oil Instrument Technologies, Procedures for Preparing a Ferrogram, Standard Oil Co., Solon, OH (1981).
6. Standard Oil Instrument Technologies, Direct Reading Ferrograph Operator's Manual, Standard Oil Co., Solon, OH (1986).
7. Kline, S. J. and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments," *Mechanical Eng.* 75 (1) 1953, 3-8.
8. Wright, R. L. and Centers, P. W., "Effect of Sample Volume on Quantitation of Ferrographic Data," AFWAL-TR-88 (Public Release Pending).
9. Price, A. L. and Yardley, E. D., "The Evaluation of the Rotary Particle Depositor in the Monitoring of Gear Transmissions Used Underground," *Maint. Management Int.*, 5 (3), 1985, 197-202.
10. Centers, P. W. and Price, F. D., "Simultaneous In-line Wear and Lubricant Condition Monitoring," *Int. Conf. on Condition Monitoring*, University College of Swansea, March 31-April 3, 1987.